Extracting gluon Sivers effect with the single spin asymmetry at the Electron-Ion Collider

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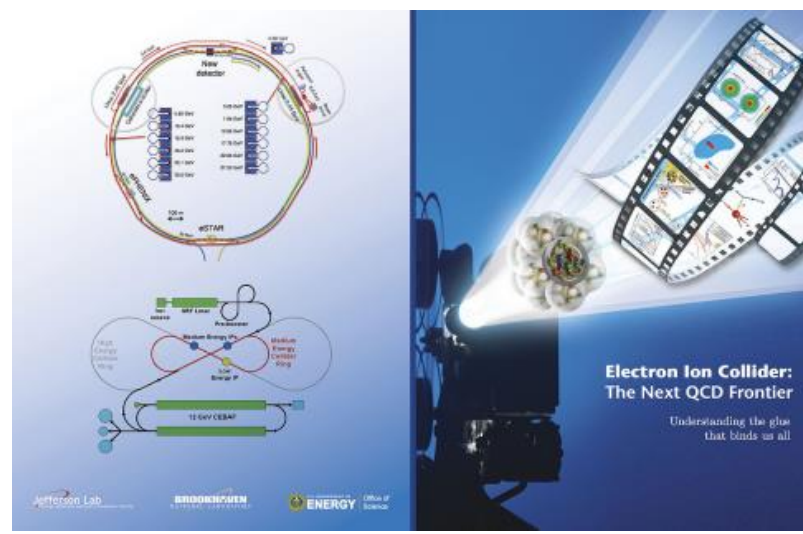

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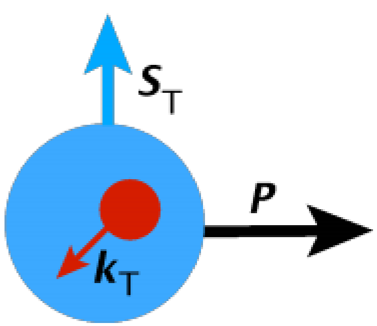
Content

- Nucleon structure and Sivers effect
- Accessing Sivers function in SIDIS
- Gluon Sivers asymmetries at an EIC
- Summary

Nucleon structure and Sivers function

- Collisions on the hadronic objects as incoherent superposition off partonic constituents.
- TMD framework provides a useful tool to study spin-orbit correlations.
- Sivers function describes the correlation of k_T and S_T.

Phys. Rev. D41, 83 (1990)

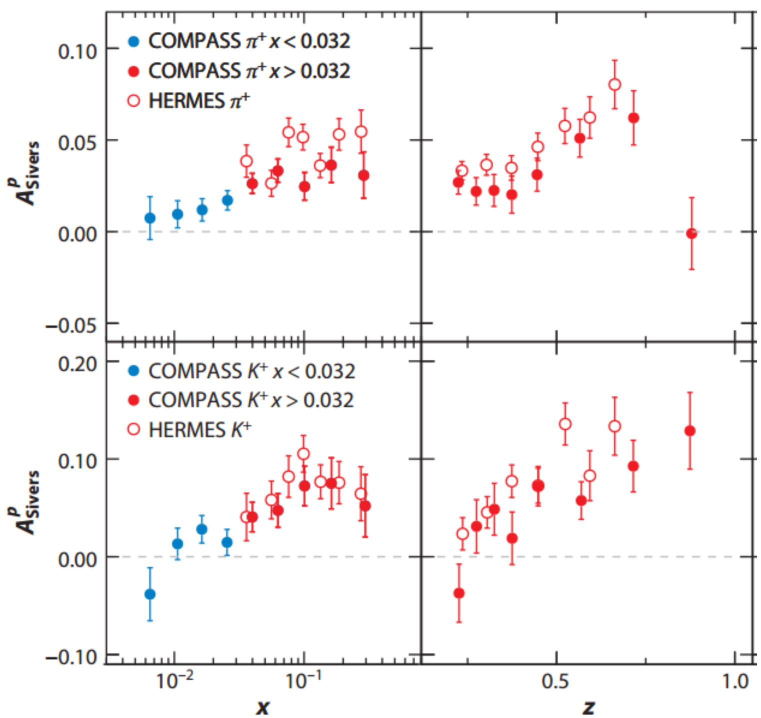


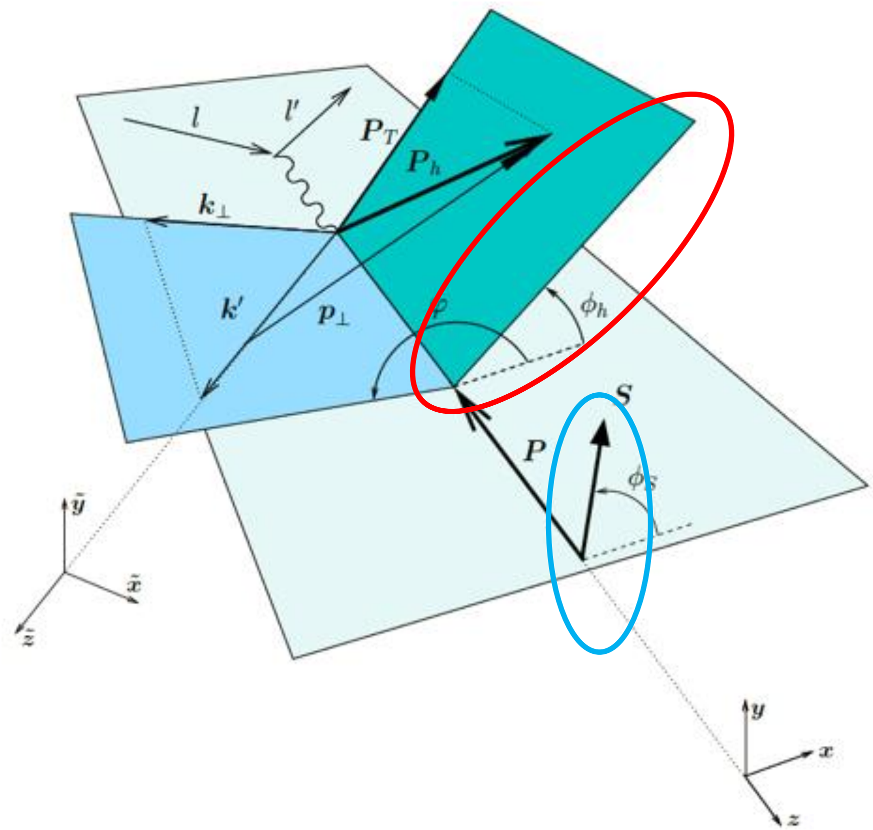
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1 \, h_{1T}^\perp$

Accessing Sivers in SIDIS

$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{hT}^2} \propto F_{UU,T} + |\boldsymbol{S}_\perp| \sin(\phi_h - \phi_S) F_{UT,T}^{\sin(\phi_h-\phi_S)} + \ldots$$

Annu. Rev. Nucl. Part. Sci. 65 429 (2015)





Extraction of quark Sivers

$$\hat{f}_{a/p^\uparrow}(x,\vec{k}_\perp) = f_1^a(x,\vec{k}_\perp;\vec{S}) = f_1^a(x,\vec{k}_\perp) - \boxed{\frac{k_\perp}{M_p} f_{1T}^{\perp a}(x,k_\perp)\vec{S}\cdot(\hat{\vec{P}}\times\hat{\vec{k}}_\perp)}$$

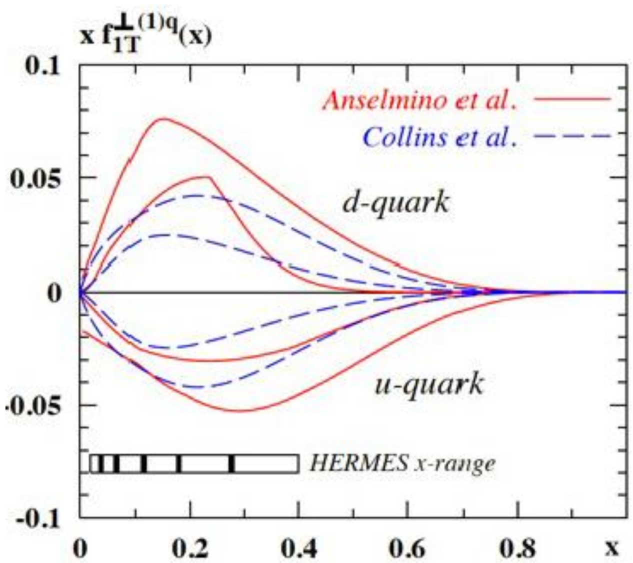
- Gaussian anzatz for transverse momentum dependence
- Sizable Sivers effect
- u, d quark Sivers with opposite sign

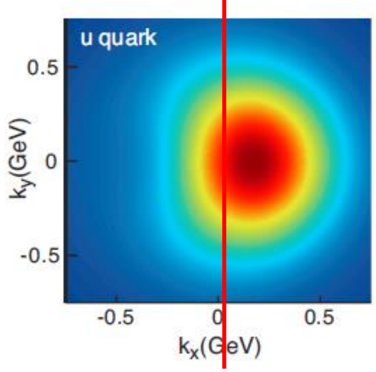
$$\Delta\hat{f}_{a/p^\uparrow}(x,\vec{k}_\perp) \equiv \hat{f}_{a/p^\uparrow}(x,\vec{k}_\perp) - \hat{f}_{a/p^\downarrow}(x,\vec{k}_\perp)$$

$$\Delta^N f_{q/p^\uparrow}(x,k_\perp) = 2\,\mathcal{N}_q^S(x)\, f_{q/p}(x)\, h(k_\perp)\, \frac{e^{-k_\perp^2/\langle k_\perp^2\rangle}}{\pi\langle k_\perp^2\rangle}$$

$$\mathcal{N}_q^S(x) = N_q^S x^{\alpha_q}(1-x)^{\beta_q}\frac{(\alpha_q+\beta_q)^{(\alpha_q+\beta_q)}}{\alpha_q^{\alpha_q}\beta_q^{\beta_q}}$$

$$h(k_\perp) = \sqrt{2e}\,\frac{k_\perp}{M}\,e^{-k_\perp^2/M^2}$$



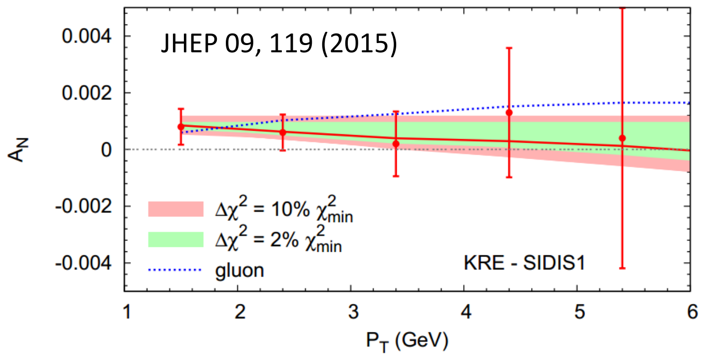


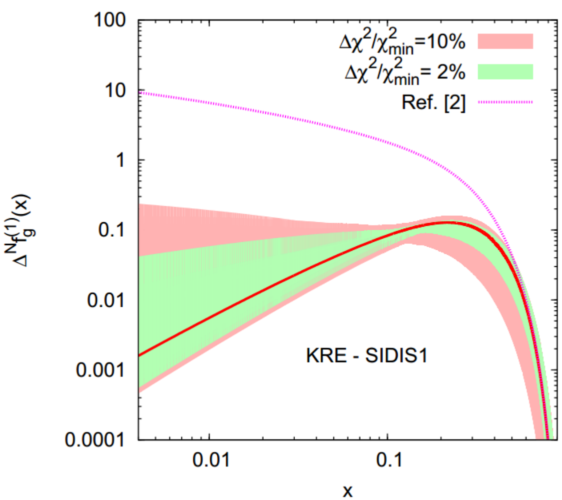
EIC white paper:
arXiv:1212.1701

Barely known for the gluon Sivers!

Current constraints on gluon Sivers

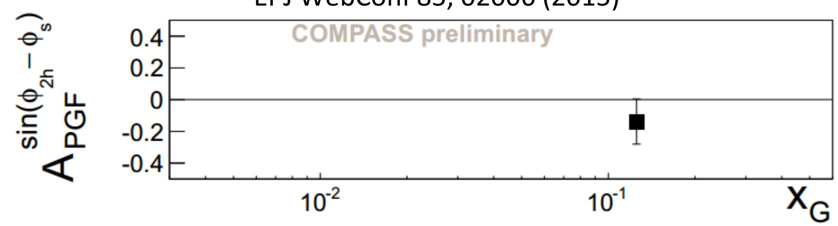
Extraction based on A_N data at RHIC





Extraction on COMPASS data

EPJ WebConf 85, 02006 (2015)



$$\mathbf{A_{PGF}^{\sin(\phi_{2h}-\phi_S)} = -0.14 \pm 0.15(stat.)}$$

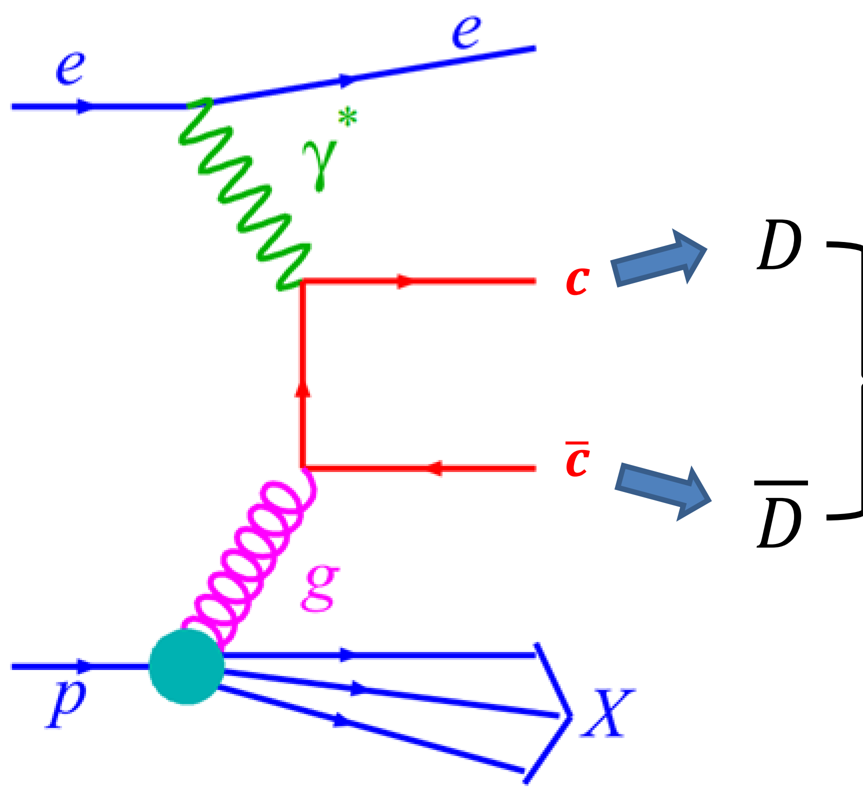
$$\langle x_G \rangle = 0.126$$

- Effective gluon Sivers from A_N may differ from the actual gluon Sivers in TMD.
- Limited x and Q^2 range explored in SIDIS. Still allow for gluon Sivers contributions of $1/N_c$.
- No hard constraints apart from the positivity bound at this moment.

Accessing gluon Sivers at an EIC

$$d\sigma^{\uparrow} = \hat{f}_{a/p^{\uparrow}}(x,\vec{k}_{\perp}) \otimes \hat{\sigma} \otimes \hat{D}_h(z) \Longrightarrow A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \frac{\Delta\hat{f}_{a/p^{\uparrow}}(x,\vec{k}_{\perp}) \otimes H_{\gamma^* g \to q\bar{q}} \otimes \hat{D}}{2 f_1^a(x,\vec{k}_{\perp}) \otimes H_{\gamma^* g \to q\bar{q}} \otimes \hat{D}}$$

- Accessing through photon-gluon fusion (PGF) process.
- Quark Sivers contribution suppressed in charm production.
- Unique measurement to probe the unknown gluon Sivers function.

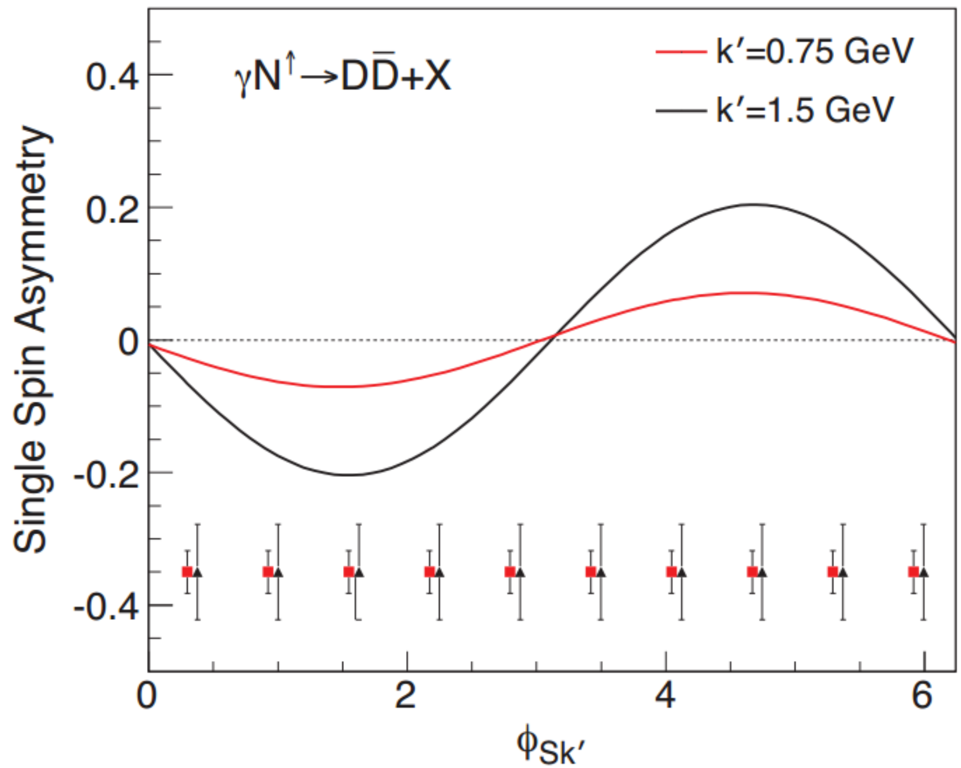


Measure a pair of D mesons

Statistically challenging!

Previously in EIC White Paper

ep 25x200 GeV
$0.05<y<0.95$
$1<Q^2<10$ GeV^2
$z_{h1}>0.25$, $z_{h2}>0.25$
$<W>=60$ GeV
$<Q^2>=4$ GeV^2



EIC white paper:
arXiv:1212.1701

Gluon Sivers with D^0 meson pair

PRD 83, 105005 (2011)
arXiv:1108.1713

TMD factorization with the correlation limit:

$$\frac{d\sigma_{\rm tot}^{\gamma^*+p^\uparrow\to h_1+h_2+X}}{dz_{h1}dz_{h2}d^2p_{1\perp}d^2p_{2\perp}} = C\int_{z_{h1}}^{1-z_{h2}} dz\frac{z(1-z)}{z_{h2}^2 z_{h1}^2} d^2\lambda_1 d^2\lambda_2 [f_1^g(x,k_\perp) - \frac{k_\perp}{M_p} f_{1T}^{\perp g}(x,k_\perp)\cos(\phi_k)]$$

$$\mathcal{H}_{\rm tot}(z,k_{1\perp},k_{2\perp}) \times \sum_q e_q^2 D_q(\tfrac{z_{h1}}{z},\lambda_1) D_{\bar{q}}(\tfrac{z_{h2}}{1-z},\lambda_2),$$

Sivers function at positivity bound:

$$f_{1T}^{\perp a}(x,k_\perp) = \frac{2\sigma M_p}{k_\perp^2+\sigma^2} f_1^g(x,k_\perp)$$

Transverse momentum dependent unpolarized term PDF with Gaussian anzatz:

$$f_1^g(x,k_\perp) = \frac{e^{-k_\perp^2}}{\pi\sigma^2} f(x)$$

$$D(z,\lambda) = D(z)\exp(-\lambda^2/\sigma^2)/\pi\sigma^2$$

Correlation limit:

$P_T' = |\mathbf{P}_T^{h1} - \mathbf{P}_T^{h2}|/2$

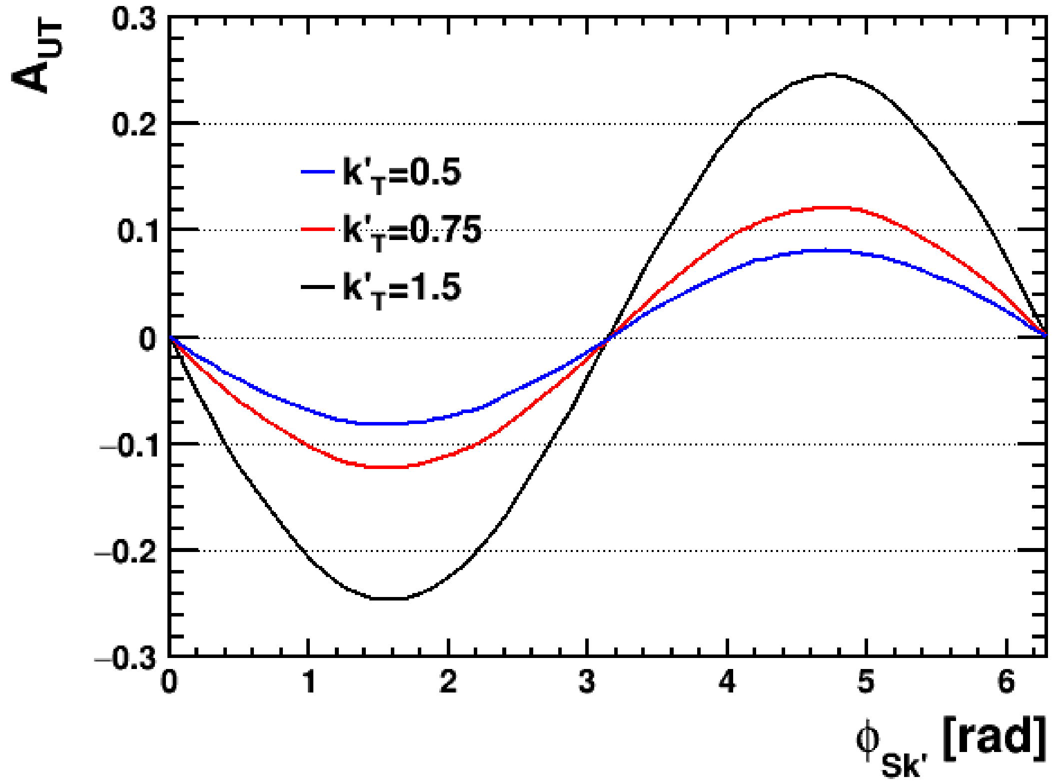
$k_T' = |\mathbf{P}_T^{h1} + \mathbf{P}_T^{h2}|$

$k_T' \ll P_T'$

Gluon Sivers with D^0 meson pair

$$A_{UT} = \frac{d\sigma^{\uparrow}(k'_T, \phi_{Sk'}) - d\sigma^{\downarrow}(k'_T, \phi_{Sk'})}{d\sigma^{\uparrow}(k'_T, \phi_{Sk'}) + d\sigma^{\downarrow}(k'_T, \phi_{Sk'})}$$

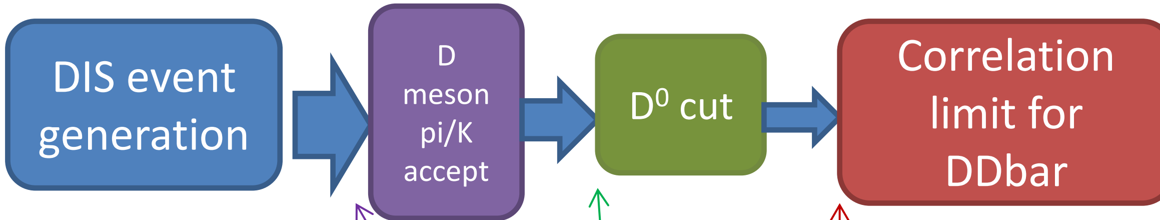
Kinematics:
W=100 GeV
Q^2=4 GeV^2
$z_{h1}=z_{h2}=0.3$
4 GeV < P_T'< 10 GeV



Gluon Sivers results in the single spin asymmetry depending on azimuthal angle between k_T' and spin direction.

$$\phi_{Sk'} = \phi_S - \phi_{k'_T}$$

Experimental considerations



Branching ratio: 3.8%

$$D^0(c\bar{u}) \to \pi^+(u\bar{d})K^-(s\bar{u})$$

$$\bar{D}^0(\bar{c}u) \to \pi^-(\bar{u}d)K^+(u\bar{s})$$

Event sample summary:
ep 25x200 GeV
sqrt(s)=141 GeV
0.01<y<0.95
$1<Q^2<20\ \mathrm{GeV}^2$

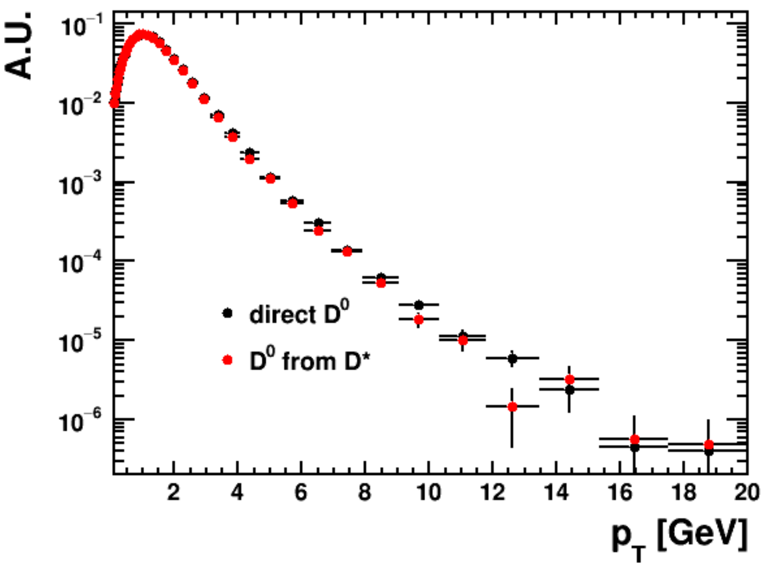
σ_{tot}=562.78 nb (all events)
σ_{cc} = 12.15 nb (PGF with ccbar)
$\sigma_{cc}^{\text{D0 inclusive}}$= 15.4 nb (D0 no cut in PGF ccbar)
$\sigma_{\text{DDbar pair}}$ = 6.3×10^{-4} nb (after all cut)

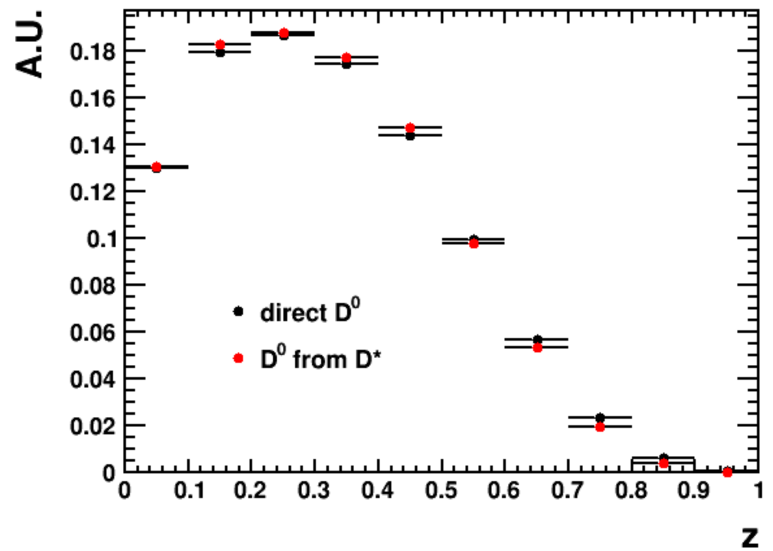
Kinematic cuts:
Pi/K cut:
Within acceptance $|\eta|<4.5$
p(K)>0.2 GeV

D^0 cut:
z>0.25
Within acceptance $|\eta|<4.5$

Correlation limit:
$k_T' < P_T'/2$

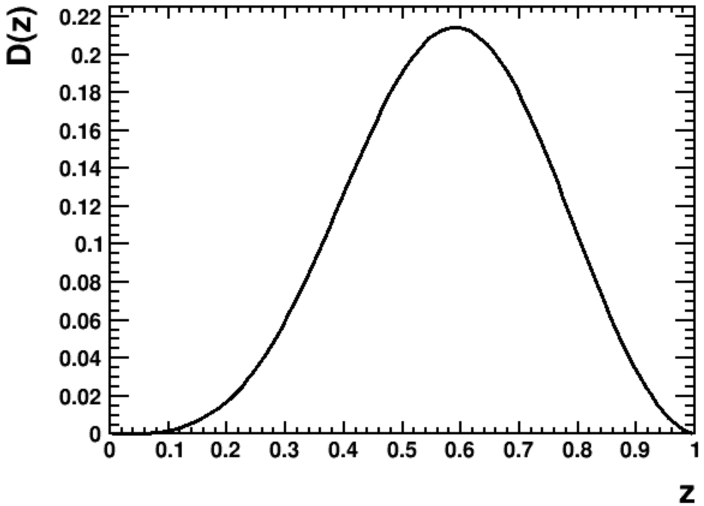
D^0 feed-down from D*

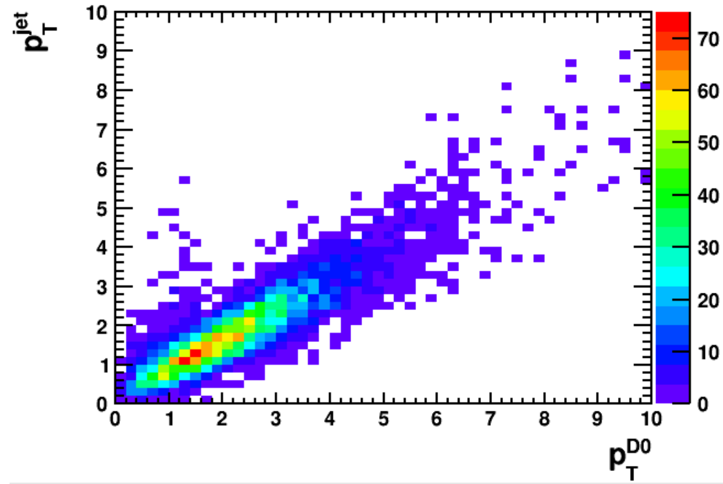


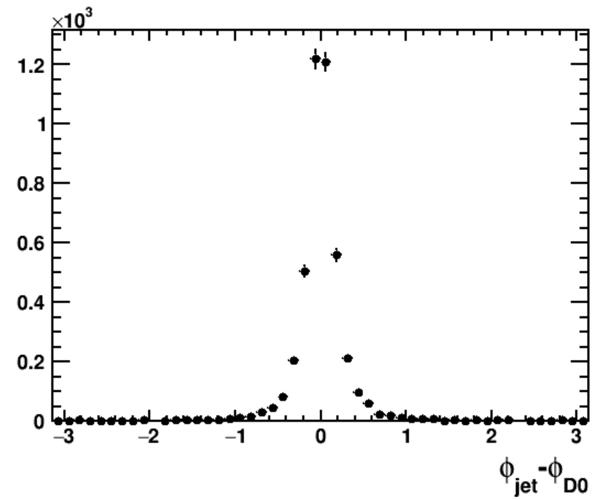


D^0 from D* decay similar to the directly generated D^0s, therefore all D^0s are analyzed.

D^0 as charm jet proxy



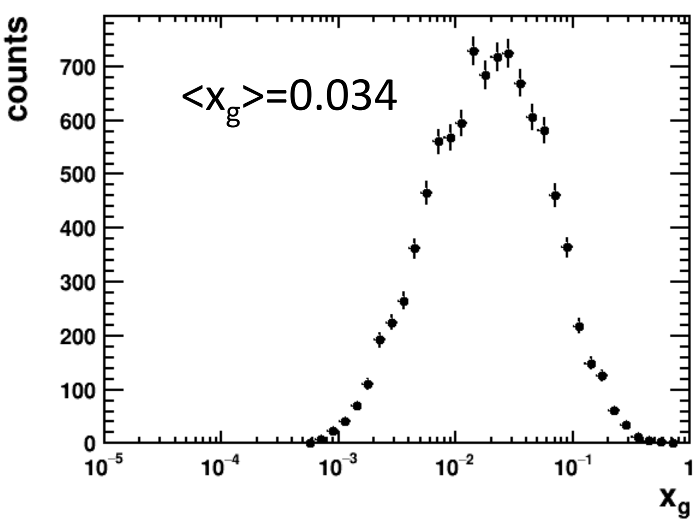




D meson takes a large fraction of the charm jet energy, serves as a proxy to the charm jet information.

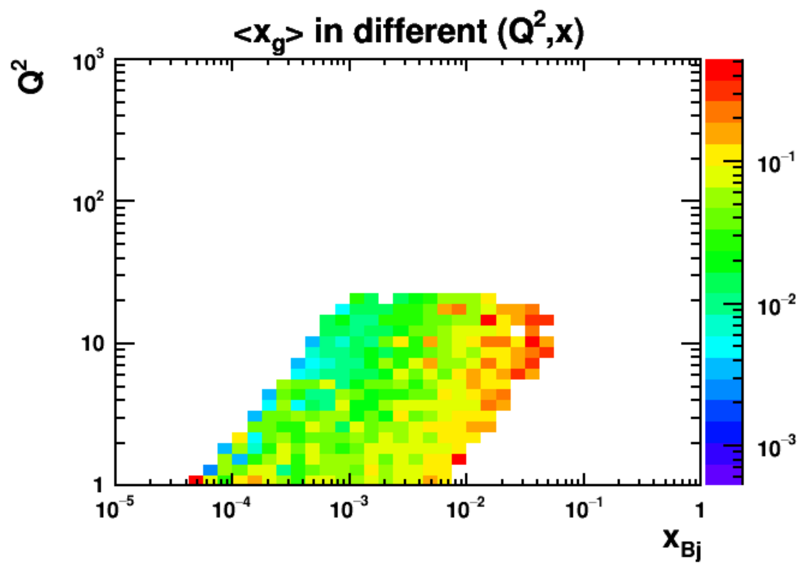
Explored gluon dynamics by the selected pairs

x_g distribution probed by the D meson pairs, overall average x_g around 10^{-2}.



$\langle x_g \rangle$ shown for every Q^2-x_{Bj} bin.

Large W ~ small x_g down to 10^{-3}.

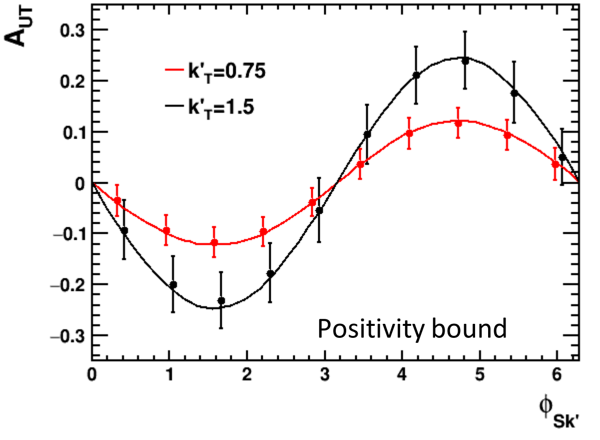


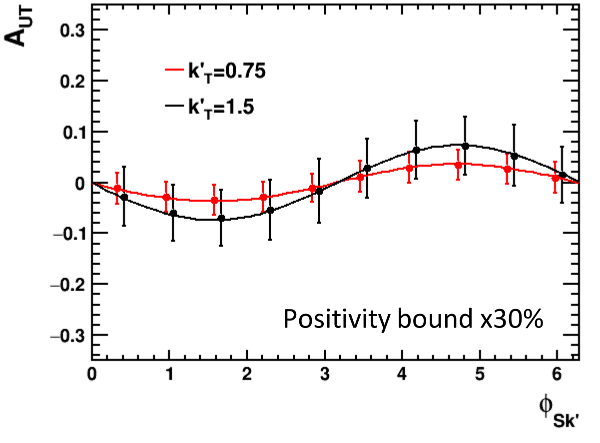
Projections for the single spin asymmetry with D meson pair

The statistical uncertainty obtained with P=70% polarization $(\delta A_{UT})^2 = \frac{1}{P^2 \sigma L} - \frac{{A_{UT}}^2}{\sigma L}$

ep 20x250 GeV
$1<Q^2<20$ GeV^2
$0.01<y<0.95$

- Integrated luminosity: 100 fb^{-1}. Correspond to 231.5 days running without run efficiency correction at L_{inst}= 5x10^{33}cm^{-2}s^{-1}.
- Red: $0.5<k_T<1$ (PGF purity: 92%)
- Black: $1<k_T<2$ (PGF purity: 96%)



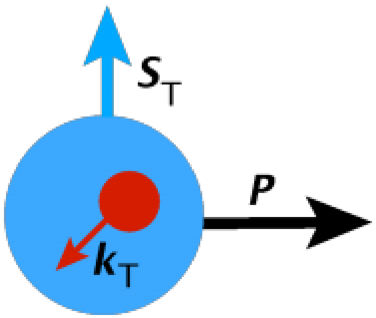


Summary

- Understanding Sivers effect is crucial for the fundamental QCD test.
- The EIC will be a unique facility to explore the gluon Sivers.
- D meson pair at the EIC is a feasible measurement sensitive to the gluon Sivers.
- Similar technique can be extended to dihadron/dijet process in DIS to provide independent handles on gluon Sivers.

Backup

Sivers function



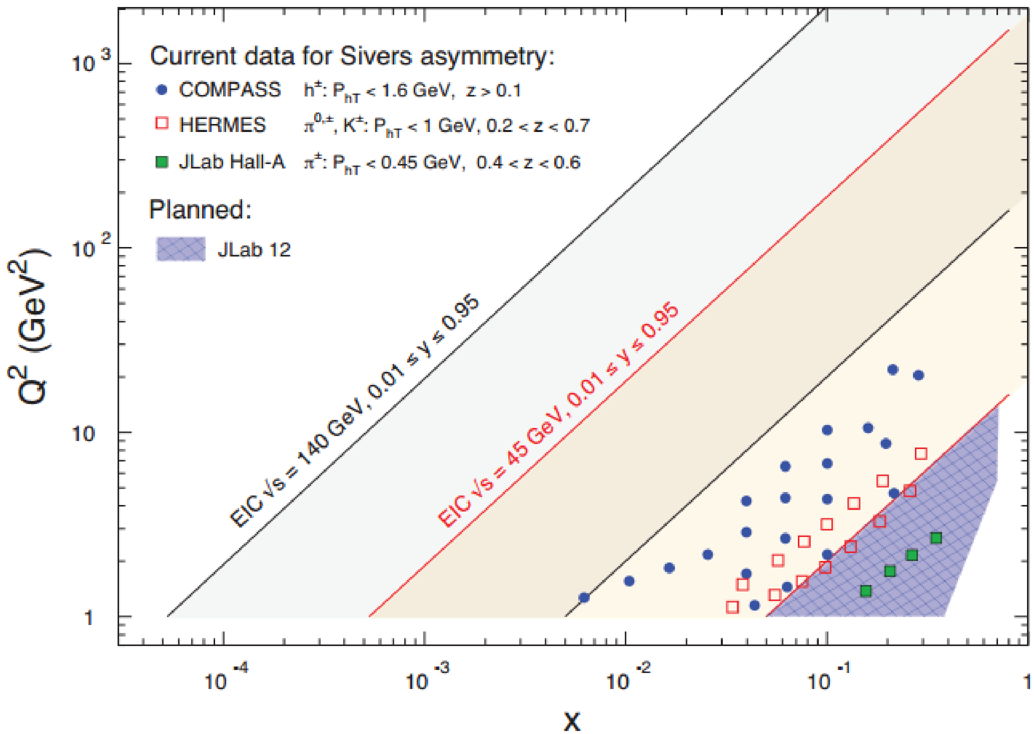
$$\hat{f}_{a/p^\uparrow}(x,\vec{k}_\perp) = f_1^a(x,\vec{k}_\perp;\vec{S}) = f_1^a(x,\vec{k}_\perp) - \boxed{\frac{k_\perp}{M_p} f_{1T}^{\perp a}(x,k_\perp)\vec{S}\cdot(\hat{\vec{P}}\times\hat{\vec{k}}_\perp)}$$

- Proposed by Sivers to explain left-right asymmetry in polarized pp collisions.
- Correlation of k_T and S_T .
- Requires initial/final state interaction, gauge link must be included in the definition.
- Naively T-odd

$$f_{1T}^{\perp a}(x,k_\perp)_{SIDIS} = -f_{1T}^{\perp a}(x,k_\perp)_{DY}$$

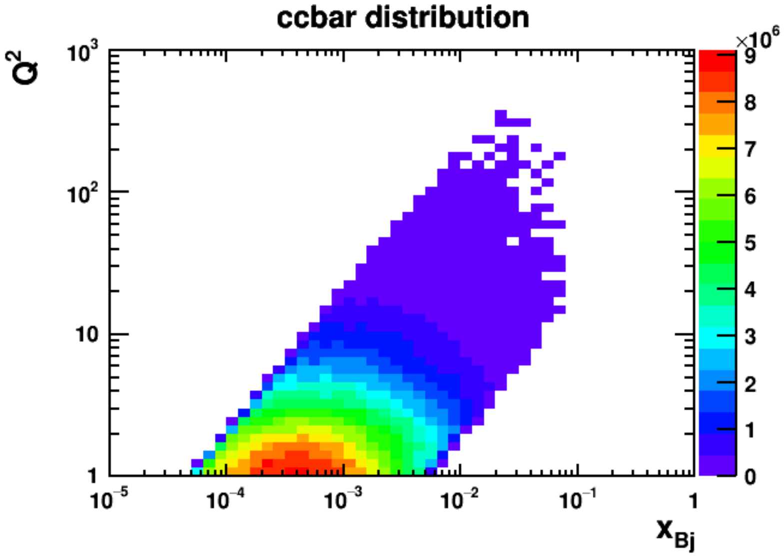
Sivers with the Electron-Ion Collider

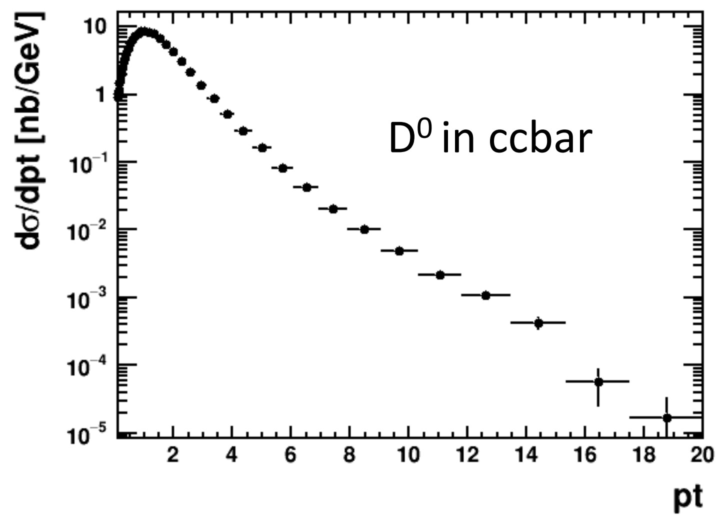
- Requirements on collider
  - High Luminosity 10^{33}-10^{34} $cm^{-2}s^{-1}$.
  - Flexible center of mass energy.
  - Polarized beams: e, p, d, ^{3}He
- Requirements on detector
  - a wide acceptance detector with good PID (e/h and π, K, p).

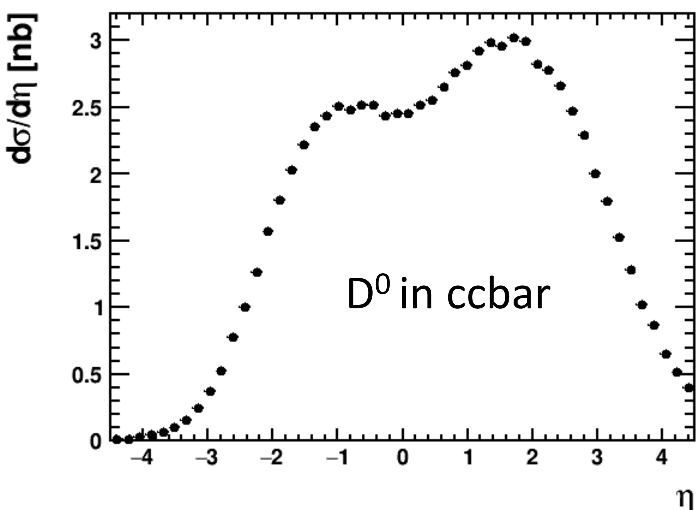


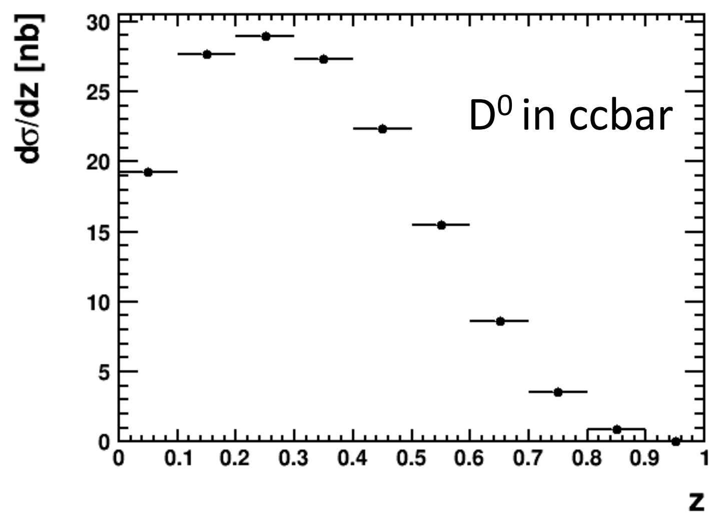
Largely extend the kinematic coverage to sea quark, gluon regime.

Inclusive D^0 production in PGF process



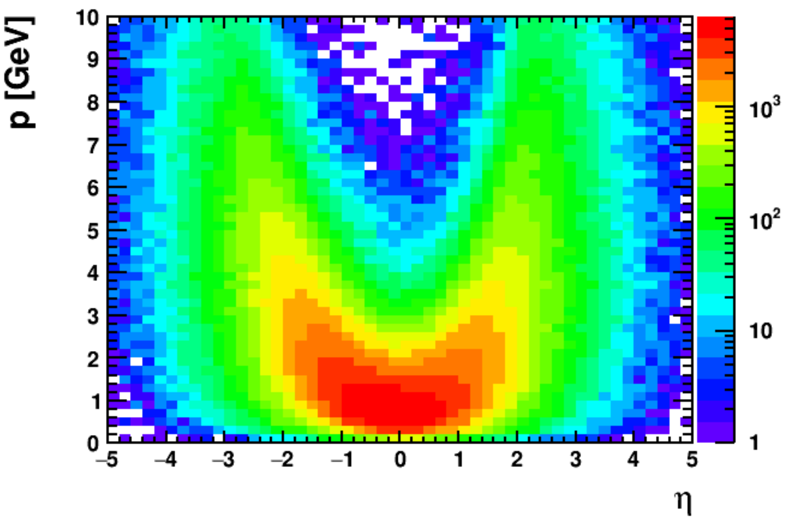




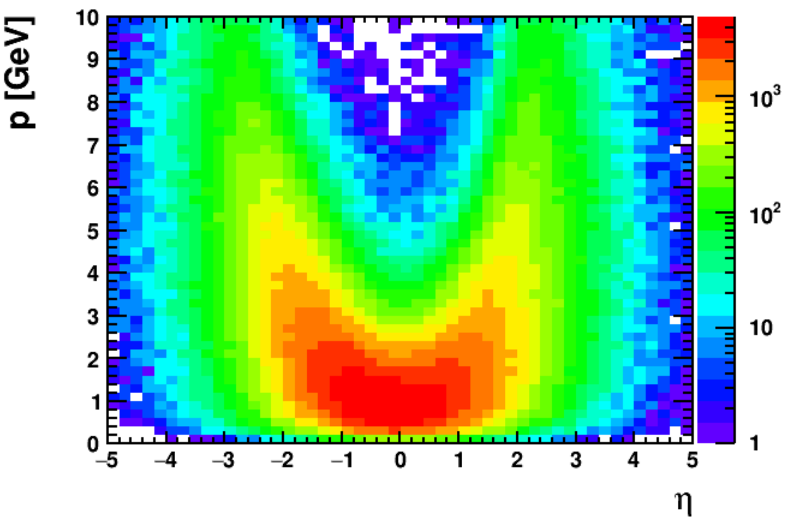


Pi/K from D^0 decay

Pion

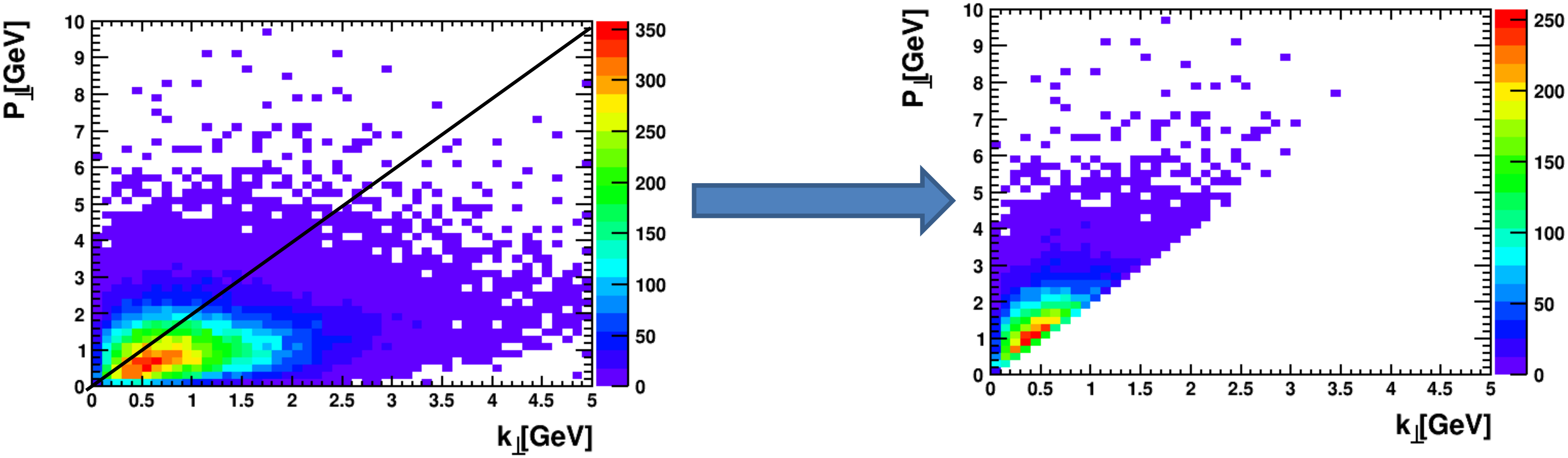


Kaon



Rejection fraction by correlation limit

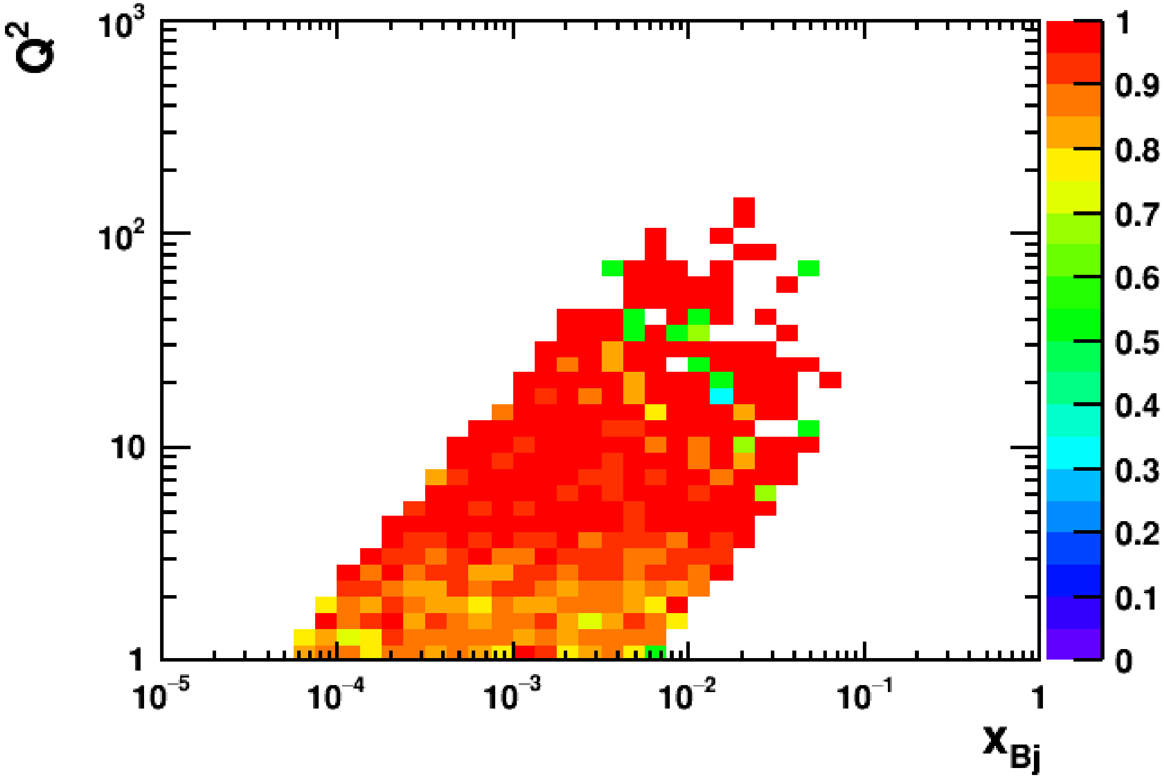
Correlation limit cut:
$k_T'/P_T'<0.5$
Survival rate: 25.8%



Purity of this measurement

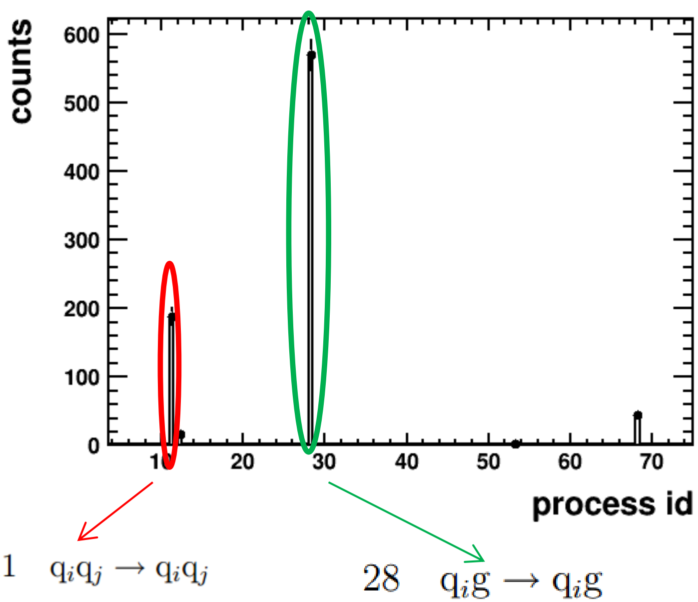
$$\text{Purity} = \frac{\text{Num D Pair in PGF ccbar}}{\text{Num D Pair total}}$$

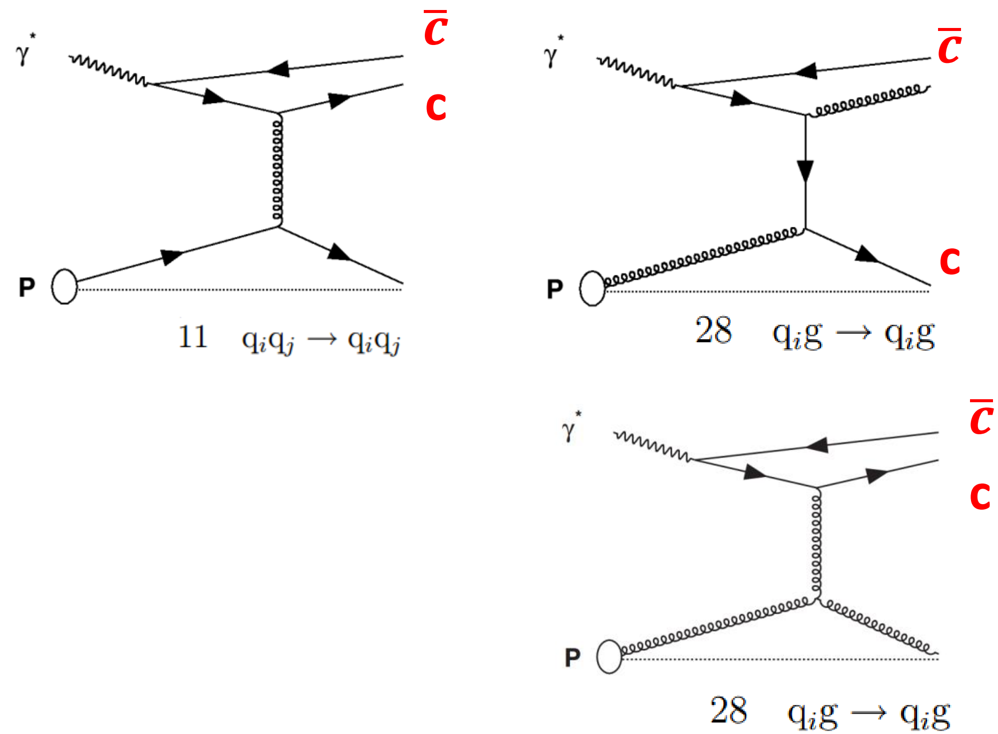
Purity of most bins around 90%, background mainly exists in low Q^2 bins.



Background process analysis

Processes contribute to the D meson pair not labeled as PGF.





quark-quark channel (11) can be counted signal in TMD framework.
quark-gluon channel (28) is a higher order effect.